SWITCHING VOLTAGE REGULATOR BASICS — PART 1

Weighing The Options

by TJ Byers

Most electronic equipment operates from low-voltage DC. Traditionally, the solution has been a power supply made of a 50/60-Hz step-down transformer followed by a rectifier and a linear voltage regulator, like an LM350. The weight and bulk is large, the heat beyond that of Death Valley, and the efficiency low (about 60%).

• • •

As equipment grows more portable, slimmer, lighter, and sexier, though, these numbers are unacceptable.

Along with more numerous high-current, low-voltage requirements comes zero-glitch load switching and increased efficiency that characterize power-down standby modes to conserve battery power, size, and weight. No longer is the standard wall adapter (brick) able to meet these demands.

Reduced size, flexible output options, and high efficiency have made switching regulators the power supply of choice for today's equipment.

Unlike linear regulators, which regulate by converting excess voltage into heat, switching regulators adjust the output voltage by using a method called pulse-width modulation.

In this article — the first of two parts — I'll show you how the industry converts voltage from one value to another without wasting power using switching converters. Better yet, I'll show you how to do it yourself.

Topology Choices

Choosing the right switching topology can be challenging. There are a surprising number of choices, each with merits and drawbacks. The most popular topologies are:

Buck: Reduces a high DC voltage to a lower DC voltage.

Boost: Increases a low DC voltage to a higher DC voltage.

Flyback: Generates an output voltage that is lesser or greater than the input, including multiple output voltages.

Invert: Generates a DC voltage which is opposite in polarity to the input voltage.

As you see, more than one topology can be used to solve the same problem. For example, a flyback configuration provides buck, boost, and invert, as well as multiple outputs. However, buck regulators may be used as inverters, and many boost regulators can provide multiple outputs. In the following discussion of these four topologies, application information will be provided, along with circuit examples. Remember, this article is cut into two parts. The buck and boost come first, followed by the flyback and invert.

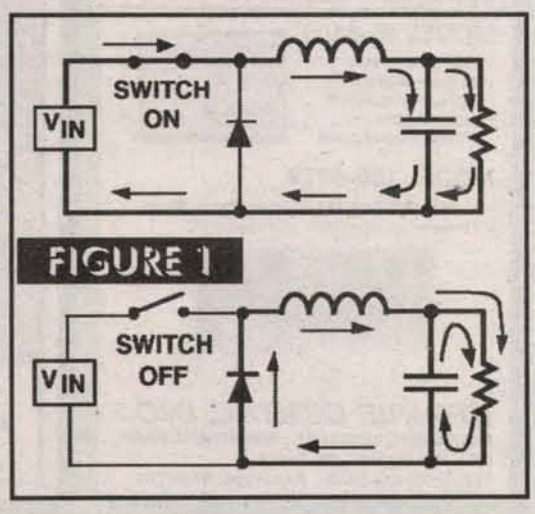

FIGURE 1

Buck Converter

The most popular switching regulator is the step-down buck convert-

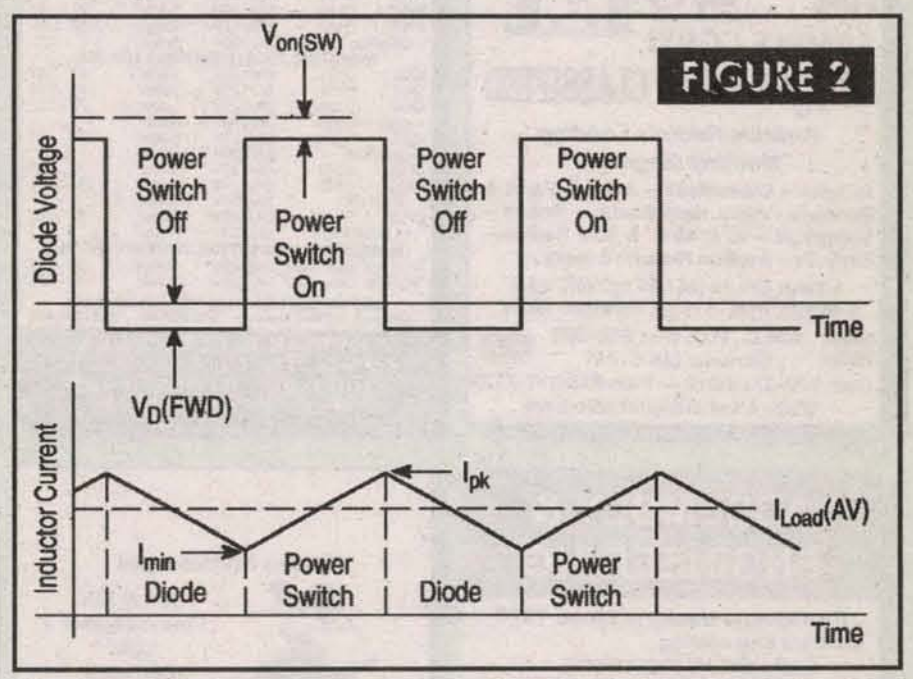

FIGURE 2

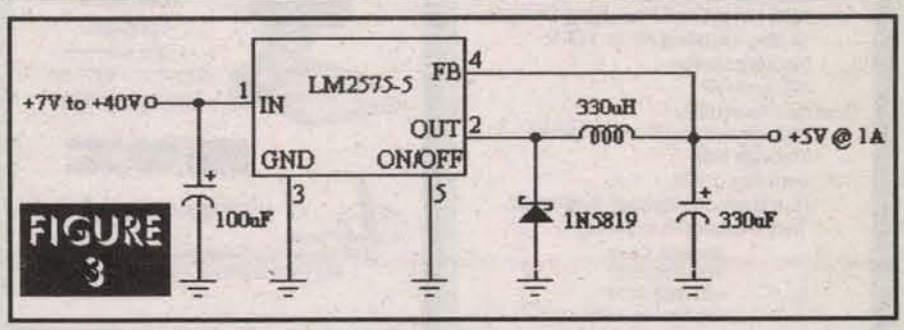

FIGURE 3

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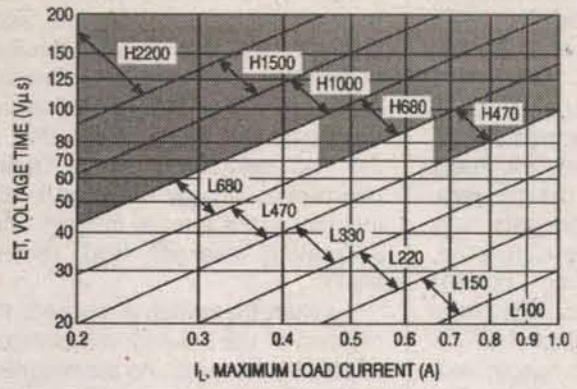

FIGURE 4

LM2575

Inductor Selection Guide

Inductor Code	Inductor Value	Pulse Eng	Renco	AIE	Tech 29
L100	100 µH	PE-92108	RL2444	415-0930	77 308 BV
L150	150 µH	PE-53113	RL1854	415-0952	77 358 BV
L220	220 µH	PE-52626	RL1953	415-0902	77 408 BV
L330	330 µH	PE-52627	RL1952	415-0905	77 458 BV
L470	470 µH	PE-53114	RL1951	415-0927	-
L680	680 µH	PE-52629	RL1950	415-0928	77 508 BV
H150	150 µH	PE-53115	RL2445	415-0906	77 368 BV
H220	220 µH	PE-53116	RL2446	430-0638	77 410 BV
H330	330 µH	PE-53117	RL2447	430-0935	77 460 BV
H470	470 µH	PE-53118	RL1861	430-0934	-
H680	680 µH	PE-53119	RL1862	415-0935	77 510 BV
H1000	1000 µH	PE-53120	RL1958	415-0934	77 558 BV
H1500	1500 µH	PE-53121	RL1868	415-0932	-
H2200	2200 µH	PE-53122	RL2448	415-0943	77 610 BV

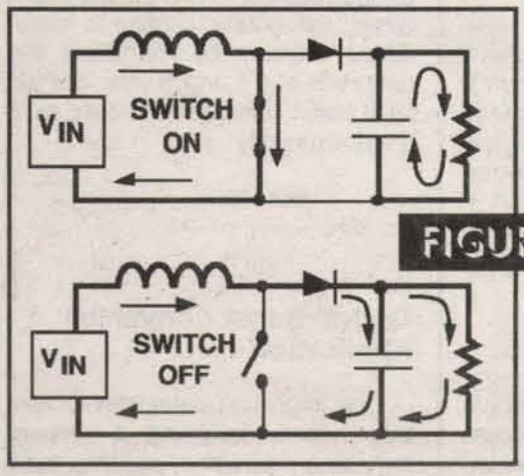

FIGURE 5

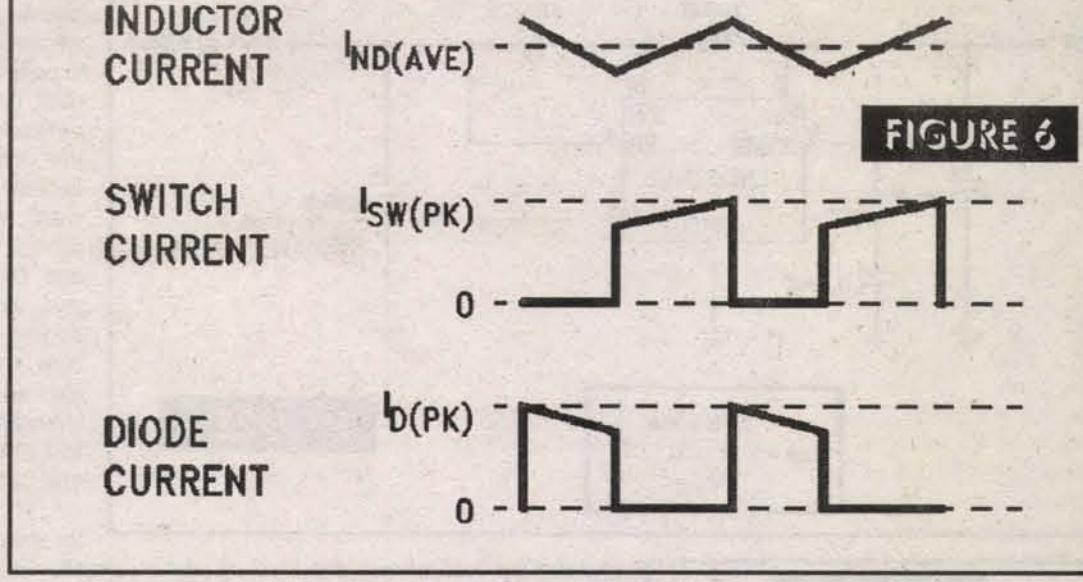

FIGURE 6

er, which converts a high DC voltage to a lower DC voltage of the same polarity. This regulator is an essential part of a distributed power system where 24 or 48 volts is stepped down to 5 or 12 volts for local board use.

The buck converter has a switch that alternately connects and disconnects the input voltage to an inductor (Figure 1).

When the switch is on, current flows through the inductor into both the load and output capacitor, during which time energy is stored in the inductor in the form of magnetic flux (an increasingly stronger magnetic field).

When the switch is opened, the input voltage is removed. Without sustained input current, the magnetic field begins to collapse, inducing a voltage in the inductor as the magnetic flux lines cut across the windings that now maintain a forward current flow through the load, output capacitor, and diode.

Simultaneously, the capacitor discharges through the load, contributing to the total current supplied to the load. After a timed period of discharge, triggered by the feedback input, the switch again turns on and rebuilds the magnetic field.

The ratio between the time on and time off is called the duty cycle, which is mathematically defined as

$$d = \frac{ton}{ton + toff}$$

In a buck converter, the voltage is held constant by controlling the duty cycle. For the ideal buck converter, the duty cycle can be described as

$$d = \frac{Vin}{Vout}$$

Figure 2 shows the idealized waveforms for a buck converter.

Typical Buck Converter Application

Unlike buck converters of yesteryear, which needed lots of outside compensation help, most of today's buck converters are five-terminal devices that require just three external components: a switching diode, inductor, and capacitor. For our example, I've selected an LM2575 from National Semiconductor (Figure 3). (You can download an LM2575 data sheet from http://www.national.com/pf/LM/LM2575.html).

For good measure (and circuit design smarts), a bypass capacitor is typically hung on the input pin. This input bypass capacitor is needed to prevent large voltage spikes at the input (caused by the switching action) and, to be effective, must be located as close as possible to the IC's input and ground pins using very short leads.

The most important parameter of this capacitor is its RMS current rating — the current density it can handle when charging and discharging. Capacitors that are physically larger, and therefore have large surface area, typically have a higher RMS current rating. In high-current applications, it's better to parallel two or more capacitors to achieve high RMS at the desired capacity.

An output capacitor has two duties: filter the output ripple and provide stability for the regulator feedback loop. Here the important factor is low ESR (Equivalent Series Resistance). Tantalum capacitors offer the lowest ESR values, which is great for filtering ripple. However, they're not so great for feedback loop stability. If the ESR value is too

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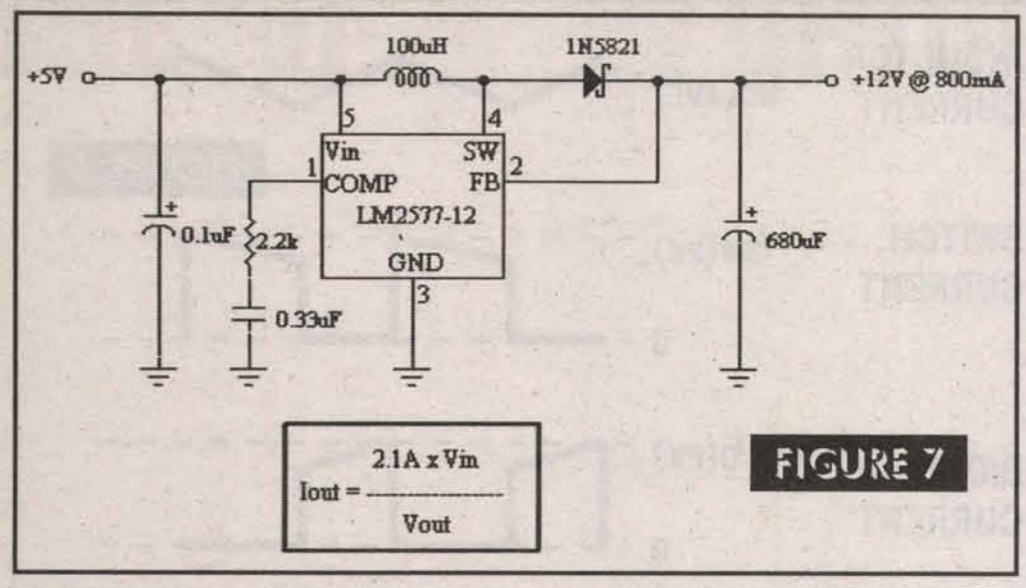

FIGURE 7

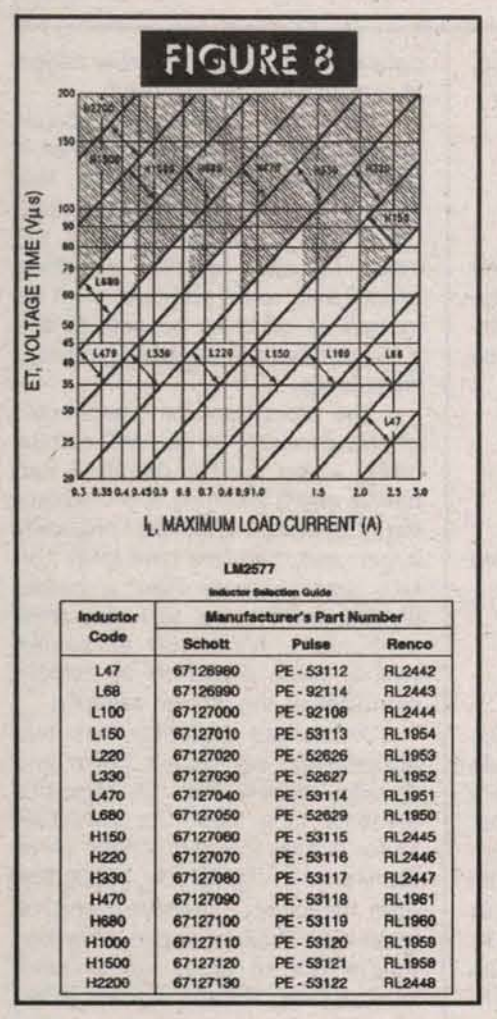

FIGURE 8

LM2577

Inductor Selection Guide

Inductor Code	Manufacturer's Part Number		
	Schott	Pulse	Renco
L47	67126960	PE - 53112	RL2442
L68	67126990	PE - 92114	RL2443
L100	67127000	PE - 92108	RL2444
L150	67127010	PE - 53113	RL1954
L220	67127020	PE - 52626	RL1953
L330	67127030	PE - 52627	RL1952
L470	67127040	PE - 53114	RL1951
L680	67127050	PE - 52629	RL1950
H150	67127060	PE - 53115	RL2445
H220	67127070	PE - 53116	RL2446
H330	67127080	PE - 53117	RL2447
H470	67127090	PE - 53118	RL1961
H680	67127100	PE - 53119	RL1960
H1000	67127110	PE - 53120	RL1959
H1500	67127120	PE - 53121	RL1958
H2200	67127130	PE - 53122	RL2448

matching the inductor to the job at hand. This magnetic component is the cornerstone of all switching regulators, and its interactive properties are elusive to even the most experienced design engineer. If the core gets magnetically over-saturated, the controlling current flattens out and the pulse-width modulator has no control of the output voltage. On the other hand, if you over-compensate by adding more iron to the core, the circuit gets sluggish and can't respond to changing load demands fast enough. Talk about a real Catch 22!

To simplify the inductor selection process, many data sheets include nomograph charts that match the inductance requirement to off-the-shelf components. Here's a typical LM2575 inductor nomograph (Figure 4).

By drawing a straight line between the voltage and current extremes (minimum and maximum), the nomograph identifies a magnetic core type and impedance value. From here, you can build (wind) the inductor yourself, or — better yet — just buy one off-the-shelf from the listed vendors (see the sidebar: Where To Buy).

low (below 0.05 ohms), the feedback loop can and will oscillate, placing a high-frequency component atop the DC output voltage. For heavy, fluctuating loads, it's recommended that you parallel aluminum electrolytics with tantalums to prevent this from happening. The value of the tantalum should not exceed 10% to 20% of the total capacitance.

The diode, often called a catch diode, provides a return path for the inductor current when the input voltage switch is open. This diode has to have a switching speed fast enough to react to the 52-KHz speed of the buck regulator, but not to be so fast that it abruptly turns off and creates EMI (Electro-Magnetic Interference) problems.

Schottky diodes provide the best switching because of their fast response time and low forward-voltage drop (0.3 volts), but ultra-fast diodes with soft turn-off — like Motorola's MUR120 — are good substitutes. Standard power supply diodes like the 1N4001 and 1N5400 are NOT suitable substitutes; don't even try it!

The trickiest part of designing a buck-converter regulator is

Boost Converter

A mirror-image of the step-down buck converter is the step-up boost converter, which converts a low DC voltage to a higher DC voltage of the same polarity. This regulator finds use in battery-powered instruments where a single 1.5-volt alkaline battery has to power a 3.3-volt cell phone, or generate a 12-volt output from an 8.4-volt source, as is the case with many laptop PCs.

In the boost configuration, the inductor is placed across both the input and output pins – and the output, rather than the input, is interrupted. See Figure 5. When the switch is turned on, current flows through the inductor only; the diode blocks current flow through the load or output capacitor at this point simply because the voltage drop across the diode junction exceeds that of the "no resistance" switch. During this period, energy is stored in the inductor in the form of magnetic flux (increasing magnetic field, remember?).

When the switch is opened, the tag end of the inductor remains connected to the input. As the magnetic field collapses, it now adds to the input voltage rather than buck it. At this point, the diode becomes forward-biased and current flows through the load while the output capacitor charges. The output voltage now equals

Vout = Vin + Vinductor

Turn the switch on again, and the diode cuts off. The inductor now rebuilds its flux field, and the output capacitor sustains current flow through the load. As in the buck converter, the output voltage is maintained constant by controlling the duty cycle of the on/off time. For the ideal boost converter, the duty cycle is approximately

$$d = \frac{Vout - Vin}{Vout}$$

Typical Boost Converter Application

An important parameter to consider when designing a step-up switching converter is the total power. Like a transformer, you can't get more power out of a boost converter than you put in. There's no such thing as a free lunch. Simply put, if you put 10 volts at 10 amps into a boost converter, you can't get more than 100 watts out (P = P x A = 10V x 10A = 100W). So, if the source is 5V at 1A, the best you can hope for at 12 volts is 400 mA.

As the voltage goes up, the current goes down: 300 mA at 15 volts, 200 mA at 24 volts, and so forth. In

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other words, a 5A boost converter will not deliver 5 amps out — it's simply the amount of current the switching transistor can force through the inductor, so size your regulator accordingly.

For our example, I chose the LM2577, a three-amp boost converter. It can boost 5 volts to 12 volts at 800 mA. For lower voltages, the current can be higher, as the formula in Figure 7 shows.

The switching action of the step-up regulator produces a triangular ripple current at the source which, in turn, causes ripple on the output. For proper operation, the LM2577 input should be decoupled with a bypass capacitor. Bypassing the input voltage pin to ground with a low ESR 0.1uF capacitor (typically tantalum) is usually sufficient. This is in contrast to the heavy input filtering recommended for the buck converter.

On the other hand, the inductor is more critical to the boost converter's performance, for more reasons than I have room to go into. Let me say that the type of core material, winding resistance, and core topology are all factors — sometimes for EMI reasons and other times for efficiency. Selecting the right boost inductor is a journey of mystic, voodoo, and sheer luck. Fortunately, there's a list of suitable inductors on the LM2577 data sheet (http://www.national.com/pf/LM/LM2577.html) that lists the pros and cons of commercially available products. Bottom line: It's hard to choose an inductor without a nomograph or software program. Here's the inductor nomograph for the LM2577.

The inductors listed here have the following characteristics:

Schott: Ferrite pot-core inductors. The benefits of this type are low EMI, small size, and very low core loss (heat dissipation). Be careful not to operate these inductors too far beyond their maximum current rating, because the core easily saturates.

Pulse: Powdered iron toroidal cores. The benefits are low EMI and the ability to tolerate peak currents above rated value better than ferrite pot-core inductors.

Renco: Ferrite, bobbin-core inductors. The benefits are low cost and the best ability to withstand peak currents above rated value. The downside is that they generate more EMI than the other two, and may interfere with sensitive equipment.

The output capacitor has less responsibility in a boost configuration than it does in a buck converter. That's because there's a compensation pin on the LM2577 and similar boost converter ICs that remove the output capacitor from the feedback loop. Instead, a zero-pole compensation (RC) network stabilizes the regulator. Two more parts, yes, but worth it. The compensation capacitor is also part of the soft-start circuitry, found in many boost converters, which gives the circuit time to ramp up to the on-off sequence before full power is applied to either the load or inductor. Can you imagine the inrush current surge consequences of applying full power to this topology with no residual flux in the inductor or charge on the output capacitor? 'Nuf said.

The switching diode in a boost switching regulator must withstand the rigors of high peak reverse voltage and fast switching, yet be soft enough to prevent switching spikes that can lead to EMI and false triggering. Gee, that sounds like a Schottky barrier diode to me. In fact, that's the only diode recommended for boost outputs up to 50 volts, with less-efficient, fast-switching diodes like the MUR110 picking up pressures at the high end.

Coming Next Month

But that makes sense because beyond 100 volts, I wouldn't use a boost converter, anyway. I'd use a flyback converter, but let's save that for next month. Meanwhile, you can obtain more information on switching regulators from the data sheets cited and the answers you'll find in this month's Electronics Q & A column. Want even more? Download the fS.pdf National Semiconductor file — a whitesheet on switching regulator technology — that's posted on our website (http://www.nutsvolts.com). **NV**

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PO110K	10K ?	.59	.56	.50
PO120K	20K ?	.59	.56	.50
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SWITCHING VOLTAGE REGULATOR BASICS — PART 2

by TJ Byers

Weighing The Options

Last month, we looked at buck and boost switching regulators — those that typically change +12 volts into +5 volts (buck converter), and +5 volts into +12 volts (boost converter). Neither are isolated from the source and have a limited convert up/down ratio. In this article, I'll show you how the industry deals with converting 110 VAC into 5 volts, 12 volts into 1000 volts, and +5 volts into -5 volts. As before, I'll provide design rules and typical applications.

In case you missed Part 1, or need your memory refreshed, here are the switching topologies that are discussed in this series.

- **Buck:** Reduces a high DC voltage to a lower DC voltage.
- **Boost:** Increases a low DC voltage to a higher DC voltage.
- **Flyback:** Generates an output voltage that is lesser or greater than the input, including multiple output voltages.
- **Invert:** Generates a DC voltage which is opposite in polarity to the input voltage.

The buck and boost were reviewed in the May '99 issue. This month's article deals with the flyback and invert configurations.

Flyback Converter

The granddaddy of all switching converters is the flyback circuit, better known to us ol'-timers as a flyback transformer. This circuit has roots that go back to the very beginning of modern electronics — back to the invention of the television, to be exact. At the heart of every TV set is a cathode ray tube (CRT) which requires a very high DC voltage — something on the order of 25 kV. Using a standard 60 Hz power transformer to generate this voltage is a bulky, heavy, and expensive proposition. To make the TV a viable consumer product, a cheaper, lighter-weight power supply was needed. Enter the flyback transformer.

The flyback converter is the most versatile of all the topologies, permitting step-up, step-down, and multiple voltage outputs. Unlike the buck and boost circuits, the flyback topology uses a real transformer, not a simple inductor. The configuration can also provide load isolation with mixed positive and negative voltage sources.

Yes, this is identical to the way a RadioShack transformer converts 110 VAC into 12 VAC and other voltages. The difference is the frequency of operation. Instead of driving the primary at 60 Hz, the switching flyback converter runs at 100 kHz and higher. The net benefits are:

- Smaller physical size
- Lighter weight
- Reduced ripple
- Tight voltage regulation
- Cheaper construction costs

The basic flyback converter is shown in Figure 1.

Essentially, this circuit works like the ignition coil under the hood of your car. When the switch

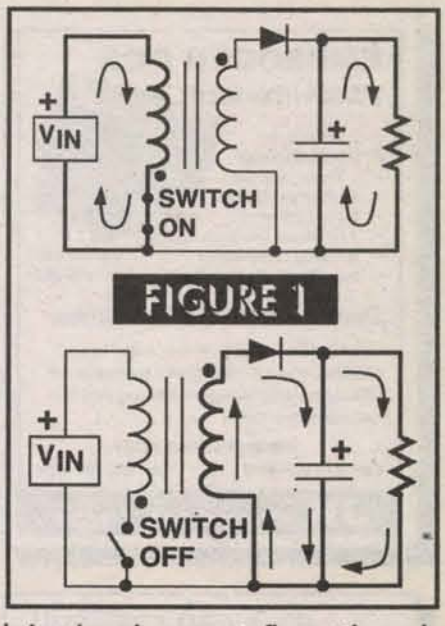

FIGURE 1

is closed, current flows through the primary of the transformer and builds up a magnetic field. When the switch is opened, the field collapses and transfers its energy to the secondary winding, inducing a voltage in that winding.

An important difference between an AC-line transformer — like a 12-volt RadioShack power transformer — and a flyback transformer is the phase relationship between the primary and secondary windings. In a power transformer, the output leaders are interchangeable. In a flyback transformer, a proper phase relationship between the primary and secondary windings (as indicated by the dots in Figure 1) is imperative for proper operation.

Note that the dotted lead of the primary winding connects to the negative terminal of the source, while the undotted lead goes to the positive terminal. This phasing is just the opposite for the secondary winding, which returns its undotted lead to the negative terminal of the source.

When the switch is turned on, a voltage of opposite polarity appears across the secondary winding — a voltage that's blocked

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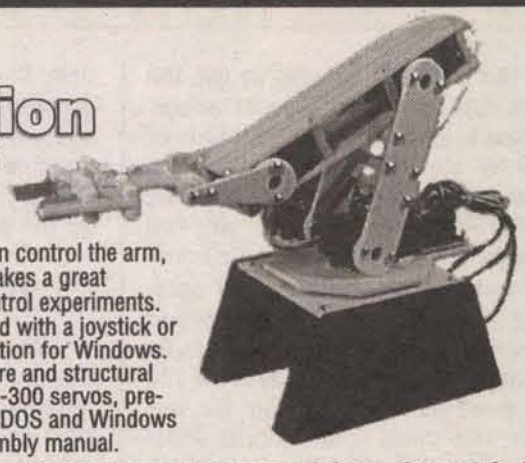

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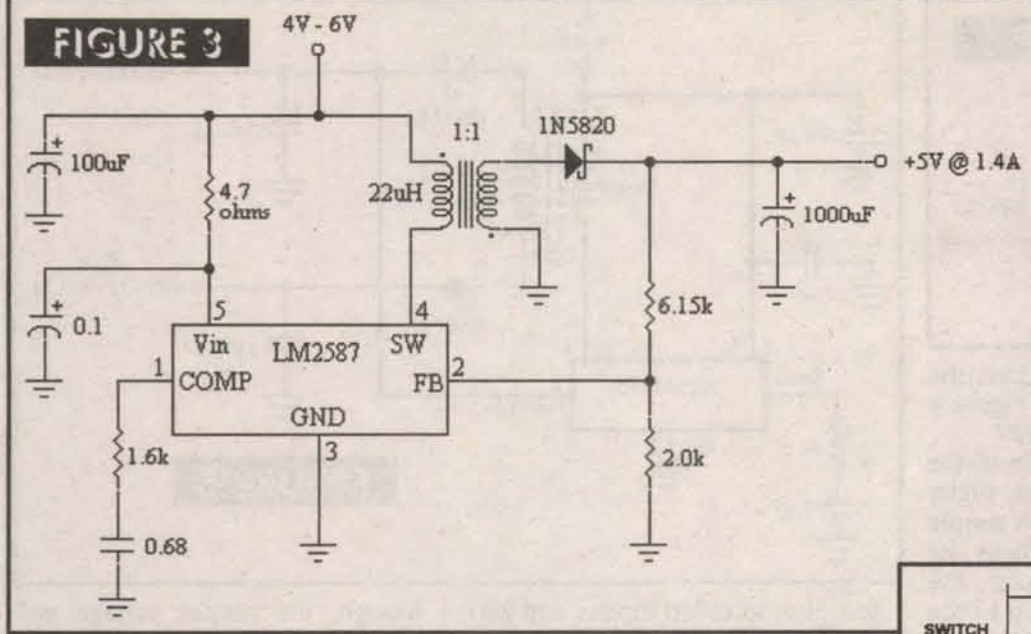
Weighing The Options

FIGURE 3



Transformers	T1	T1	T1	T2	T3	T4
V_{IN}	4V–6V	4V–6V	8V–16V	4V–5V	16V–36V	16V–36V
V_{OUT1}	3.3V	5V	12V	12V	12V	5V
I_{OUT1} (Max)	1.8A	1.4A	1.2A	0.3A	1A	2.5A
N_1	1	1	1	2.5	0.8	0.35
V_{OUT2}				-12V	-12V	12V
I_{OUT2} (Max)				0.3A	1A	0.5A
N_2				2.5	0.8	0.8
V_{OUT3}						-12V
I_{OUT3} (Max)						0.5A
N_3						0.6

FIGURE 4

LM2587
Transformer Selection Table

Transformer Type	Manufacturers' Part Numbers				
	Coilcraft (Note 15)	Coilcraft (Note 15) Surface Mount	Pulse (Note 16) Surface Mount	Renco (Note 17)	Schott (Note 18)
T1	O4434-B	O4435-B	PE-68411	RL-5530	67141450
T2	O4337-B	O4436-B	PE-68412	RL-5531	67140890
T3	O4343-B	—	PE-68421	RL-5534	67140920
T4	O4344-B	—	PE-68422	RL-5535	67140930

Note 15: Coilcraft (800-322-2645; http://www.coilcraft.com)
Note 16: Pulse Engineering (619-674-8100; http://www.pulseeng.com)
Note 17: Renco Electronics (800-645-5828; http://www.rencousa.com)
Note 18: Schott Corp. (612-475-1173; http://www.schottcorp.com)

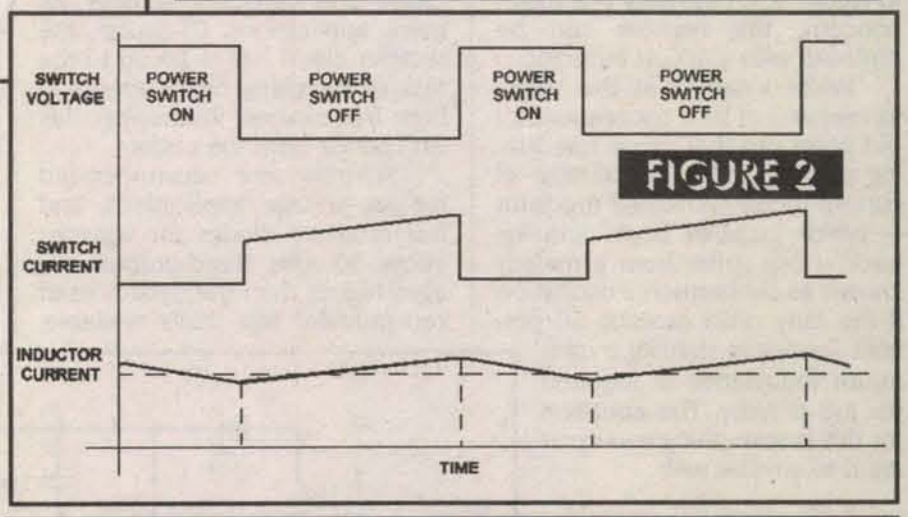


FIGURE 2

from charging the capacitor by the diode. When the switch is opened, the primary field collapses and the dotted secondary lead swings positive, which now lets current pass through the diode into the capacitor and the load.

During the next cycle, the polarity reverses again, and the capacitor provides power to the load while the magnetic field builds up. And so it goes. Figure 2 shows the idealized waveforms for a flyback converter.

Flyback Output Voltage

The secondary voltage is proportional to the number-of-turns between the primary and secondary windings. For a line-operated power transformer, the output voltage is equal to

$$Vout = Vin \times N(\text{turns ratio})$$

A RadioShack 12.6 volt transformer, for example, has a turns ratio of 10:1, whereas a 25.5 volt transformer has a 4.5:1 ratio. In both cases, there's a fixed relationship between output voltage, turns ratio, and the 110 VAC line.

Most switching flyback transformers, on the other hand, determine the output voltage by varying the amount of time current flows through the primary of the transformer. The ratio between the time the current is on and the time it's off is called the duty cycle, which is mathematically defined as:

$$d = \frac{t_{on}}{t_{on} + t_{off}}$$

In a feedback converter, the duty cycle and output voltage are determined by the following equations:

$$d = \frac{Vout}{N(Vin) + Vout} = Vout = N \times Vin \times d/(1-d)$$

where N equals the turns ratio between the primary and secondary windings.

Theoretically, the output voltage can be as large as desired – just keep increasing the turns ratio of the transformer. However, there are physical limitations that prevent the output voltage from increasing to infinity.

They include losses in the switching circuit, magnetic losses, and breakdown voltage of the insulators. Moreover, the flyback converter has the same limits of a power transformer; that is, you can't take out more power than you put in.

For example, if the input to the transformer is 5 volts and the switching current is 5 amps, the best you can hope for is 25 watts of power out (assuming no losses, of course). If the output voltage is 100 volts, the output current is just 250 mA – a far cry from the 5 amps you may have been expecting.

At some point, the ratio between higher voltage and lower current becomes unusable; infinite voltage out equals zero current out. Typically, PC-based flyback transformers have a turns ratio that ranges from 1:1 to 1:2.5.

Typical Flyback Converter Application

Flyback circuits are the most forgiving because there's no critical magnetic component as in the previous buck and boost topologies. However, the closer you can match the flyback transformer to the switching frequency and output load, the more efficient it becomes. For this exercise, I've selected the LM2587.

As always, a bypass capacitor should be placed between the input pin and ground. It should consist of a low ESR aluminum electrolytic (100 uF) paralleled

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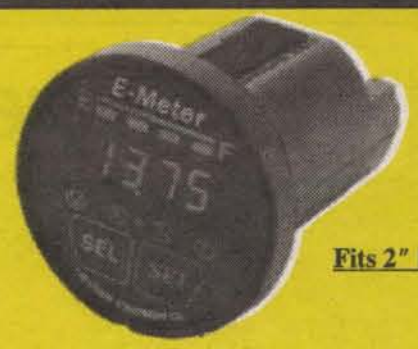

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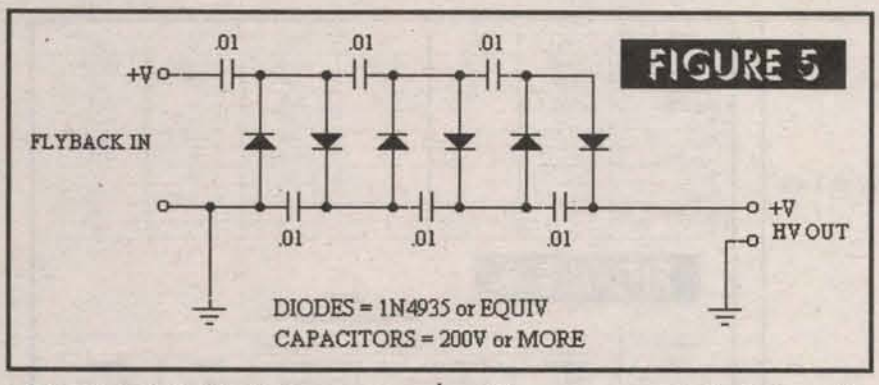

FIGURE 5

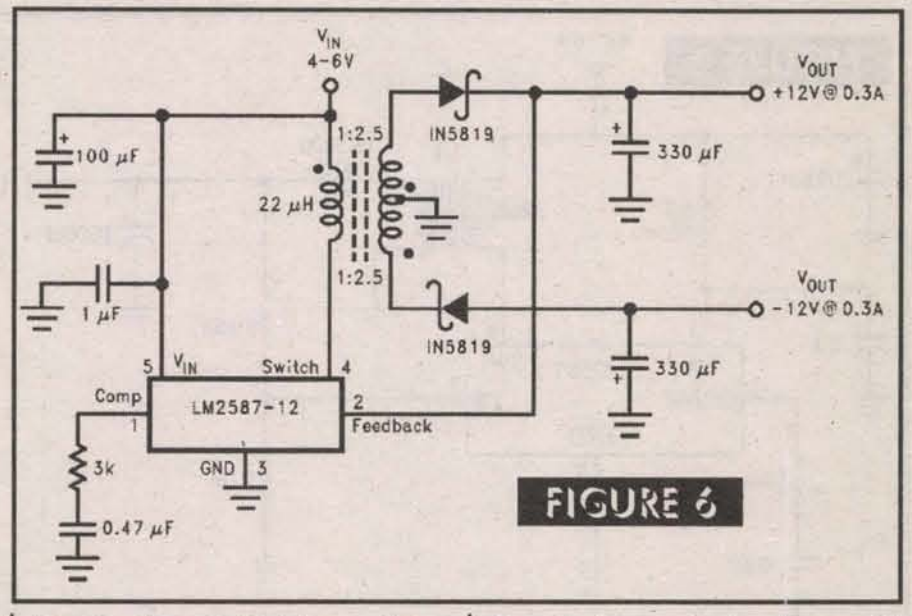

FIGURE 6

with a tantalum (1 uF). For serious applications, a small RC low-pass filter between the input pin and ground is recommended. Typically, it consists of a 4.7 ohm resistor and a 0.1 uF capacitor, as shown in Figure 3. If efficiency is a major concern, the resistor can be replaced with a 10 uH inductor.

While I said that the transformer was of little consequence, I did point out that some fine tuning was desirable. Specifically, all current-mode controlled regulator – which includes boost and flyback – can suffer from a malady known as subharmonic oscillation if the duty cycle exceeds 50 percent. To ensure stability, a minimum inductance is required for the primary. The equation for this is something you don't want to wrestle with.

$$L = \frac{2.92(Vin \times (2d-1))}{1-d}$$

where L is in uH and d is the duty cycle. To ensure stability over the full range of operation, set Vin to Vin (min) – the lowest expected input voltage – and d to d (max) (the maximum expected duty cycle). Personally I find this a lot of trouble, and so do a lot of other designers. That's why most switching regulator datasheets come with a nomograph that does the calculations for you. See Figure 4 for the table for the LM2587.

On the secondary side of the transformer, you can do pretty much what pleases you. A simple diode and capacitor suffices for many applications. Of course, the rectifier diode has to be up to the task of switching high currents at high frequencies. Remember this isn't 60 Hz from the outlet.

Schottky are recommended for low-voltage applications, and fast recovery diodes for voltages above 50 volts. Need output voltages higher than the flyback itself can provide? Yep, that's available, too. They're called triplers and you can find a bushel of them at your local TV/VCR repair shop, or you can build your own using the schematic in Figure 5.

As stated earlier, the output voltage is determined by the duty cycle of the current flowing through the primary of the transformer. Left to its own devices, though, the output voltage will vary up or down, depending on the load. As the load increases, the output voltage decreases, and visa versa. To hold the output voltage constant, a technique called pulse-width modulation (PMW) is applied to the switcher.

Basically what PWM does is adjust the duty cycle of the input pulse to control the input power, and therefore the output voltage. When peak output is required, the width of the input pulse is very wide to pack a heavier charge into the transformer. When the load is light, the input pulses are narrow, like a picket fence.

To control the PWM, a part of the output voltage is fed back to the switching controller (pin 2 of the LM2587) using a resistor divider. What the controller does is adjust the width of the switching pulse so that the voltage on this pin is always 1.23 volts – a voltage that's typical of most adjustable switching regulators, including buck, boost, and flyback.

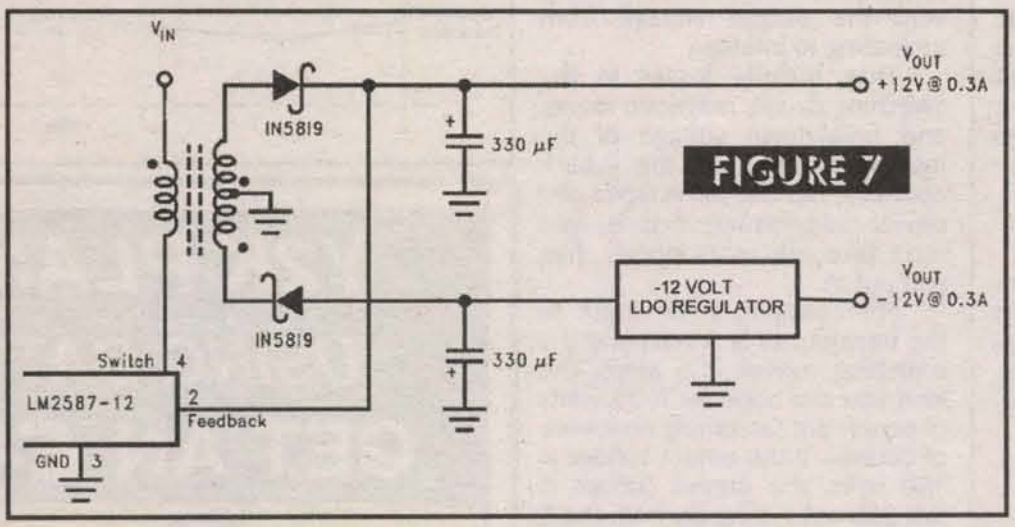

FIGURE 7

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Weighing The Options

(In a fixed-voltage regulator, like the LM2587-5.0, the divider resistors are placed on the chip inside the IC.)

If the voltage falls below 1.23 volts, it means the output voltage is sagging, which prompts the controller to increase the width of the pulse. Rising voltages on the feedback pin force a reduction in pulse width. In a well-designed converter circuit, it's not unusual to find the output voltage held to within 20 mV of nominal. Here are typical resistance divider values for popular voltages.

OUTPUT VOLTAGE	R1	R2
3.3V	3.4k	2k
5.0V	6.15k	2k
12V	8.73k	1k
15V	11.2k	1k

Generating Multiple Outputs

But we've only scratched the surface of the merits of flyback conversion. Not only can it provide a buck or a boost voltage, it can provide as many output voltages as you want using just one flyback transformer. Let's take a simple, dual-output power supply, like the kind needed for op amps (Figure 6).

Very often, op-amp circuits need a positive and negative power source. In fact, until just a few years ago, it was a requirement. Back in the days of old, these voltages were generated using a bipolar, tracking power supply, which were bulky and inefficient. While op-amp restrictions have relaxed since then, bipolar-powered circuits still have advantages over single-ended designs.

Our example starts off quite meekly as a simple flyback transformer voltage converter. In fact, the only change is in the secondary winding of the transformer, which is now center-tapped. Center-tapped transformers have been around for many years for different purposes.

Look at the power transformer options in any RadioShack catalog, and you'll see that nearly all sport a center tap. For our particular application, we're going to use that center-tap to generate a positive and a negative output voltage.

It's simple enough. We simply ground the center-tap so that the voltage is split in half, with 12 volts on the top and 12 volts on the bottom. Each half of the winding can now be treated as a separate transformer winding. On the top side, the output is run through a diode that has its anode lead connected to the transformer to produce a positive voltage. On the bottom side, the output is run through the cathode lead of a rectifying diode to generate a negative voltage. Ground is common.

The rectified outputs are typical enough, but not the PWM feedback. By design, PWM can only sense one output voltage, not multiple outputs. In our example, the feedback pin is connected to the +12 volt output. That means that this line alone will be held within about 20 mV of 12 volts. The negative output, on the other hand, is unregulated. It depends on the pulse width of the positive line.

Let's say the +12V output demands more current. This prompts a larger duty cycle to satisfy the request. Let's also say that the current demands of the -12V output remains the same. Well, I guess you can guess the results. The negative output voltage goes up – by how much is determined by the change in the duty cycle.

Fortunately, there's a simple solution which has recently appeared on the scene. It's called a low-dropout voltage regulator, or LDO. It's inserted into the circuit like this (Figure 7). Need three outputs? Here's a block diagram of how it's done (Figure 8).

As before, only one output can be regulated. If you want regulation on the other outputs, you need additional regulators. Linear LDOs are preferred over introducing another switching regulator.

Don't forget, however, that you can't get more power out than you put in, which is why PC switching power supply specs often paint a tainted picture. Let's take a common 250-watt PC power supply, for example. Typically, it lists the outputs as:

- +5V @ 30A
- +12V @ 10A
- -5V @ 1A
- -12V @ 0.5A

Added up, that comes to 281 watts, yet the power supply is only rated at 250 watts. How come? Well, it's because the outputs weren't meant to be working full-time all the time. They share.

For example, if the +5V load is drawing just 15 amps, the unused energy can be transferred to the +12V source to boost its output to about 16 amps, wiring and rectifier permitting. Just remember, altogether, they cannot exceed 250 watts.

FIGURE 8

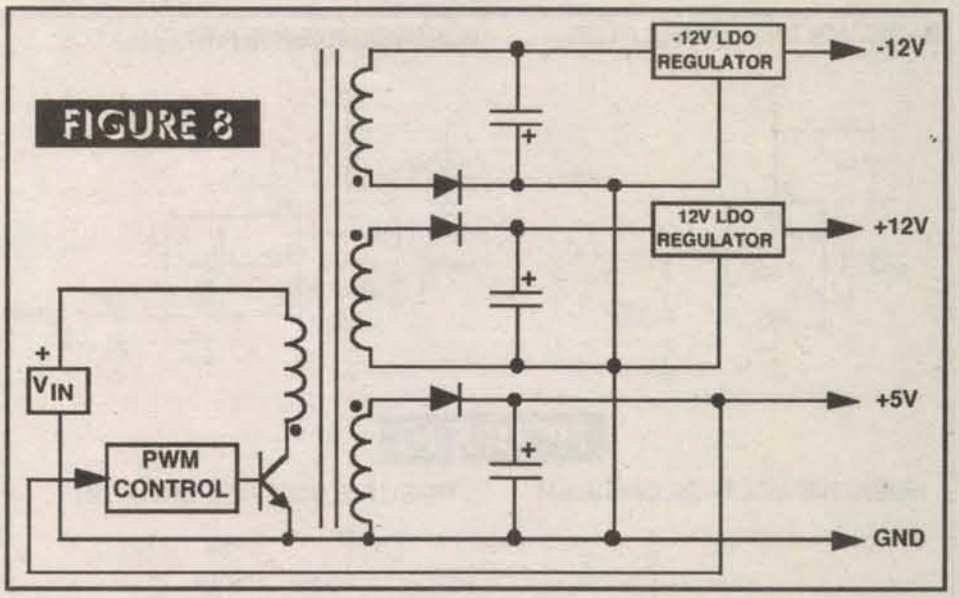
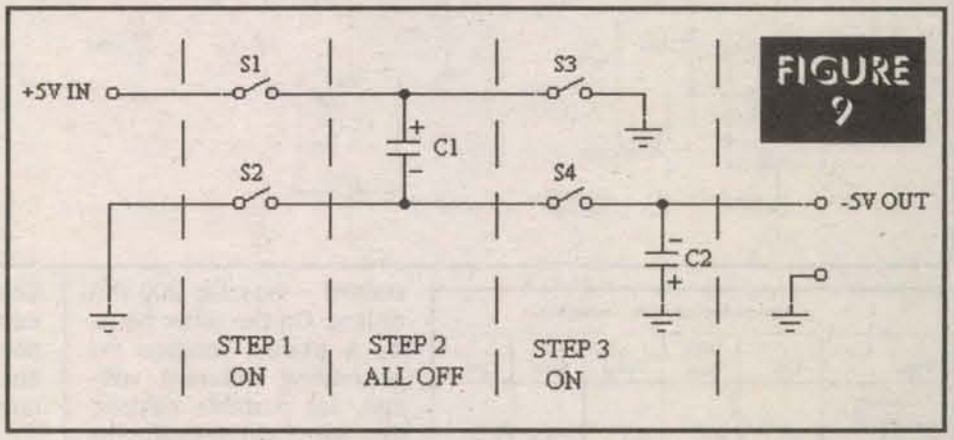
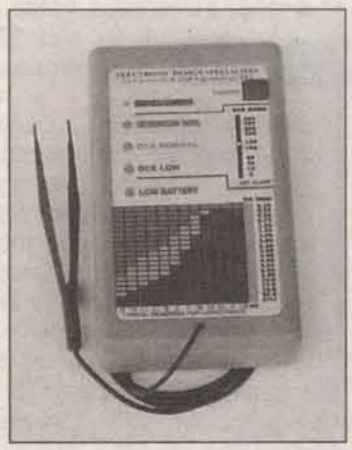


FIGURE 9



Don't be stupid.



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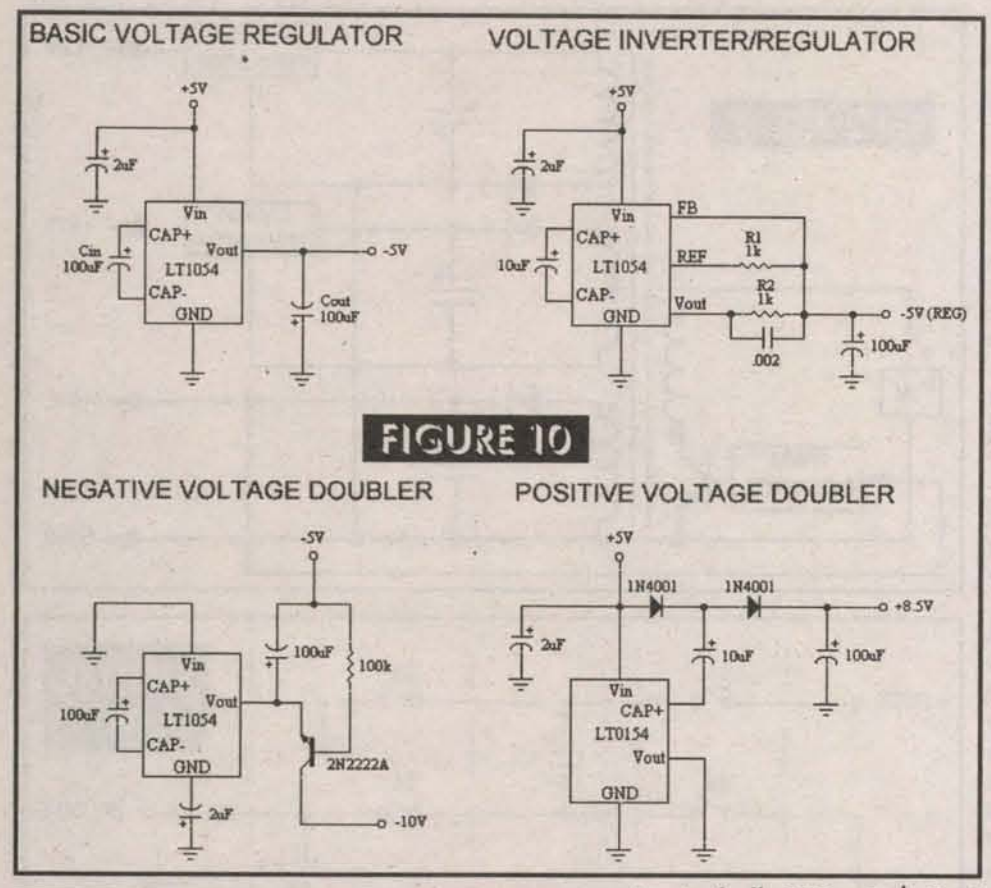

FIGURE 10

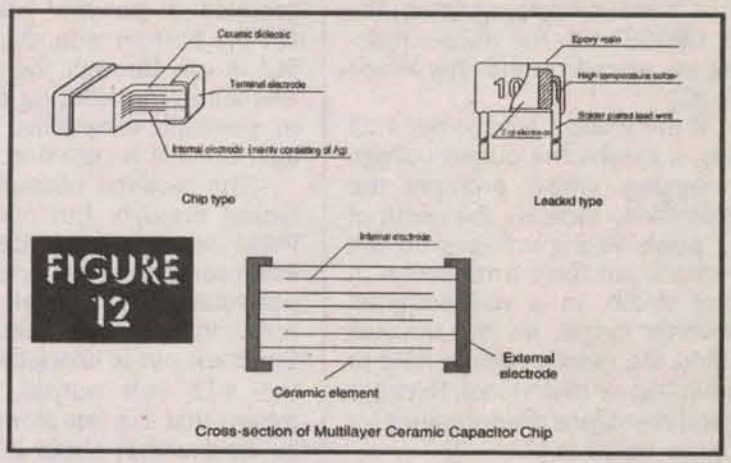

FIGURE 12

Cross-section of Multilayer Ceramic Capacitor Chip

Alternative Capacitor Technologies

Type	Life	High Freq	Temp	Size	Cost
Aluminum Electrolytic Capacitor	Fair	Fair	Fair	Small	Low
Multilayer Ceramic Capacitor	Long	Good	Poor	Fair[1]	High
Solid Tantalum Capacitor	Above Avg	Avg	Avg	Avg	Avg
OS-CON Capacitor	Above Avg	Good	Good	Good	Avg

NOTE
[1]Refer to capacitor manufacturer's data sheet for operation below 0°C.

FIGURE 11

Recommended Capacitor Manufacturers

Manufacturer	Capacitor	Capacitor Type
Sprague	672D, 673D, 674D, 678D	Aluminum Electrolytic
Sprague	675D, 173D, 199D	Tantalum
Nichicon	PF and PL	Aluminum Electrolytic
Mallory	TDC and TDL	Tantalum
TOKIN	MLCC	Multilayer Ceramic
MuRata	GRM	Multilayer Ceramic

Inverting Regulator

Sometimes called a buck-boost converter, the inverting regulator takes a DC voltage and changes it to a voltage of opposite polarity. Furthermore, the voltage can be higher or lower than the input. More often than not, though, the output is a mirror image of the input.

Unlike the converters described above – all of which rely on magnetics – inverting regulators normally use switched capacitors to accomplish their goal. The correct term is called charge-pump, but switched-capacitor is the most popular term used. While the weight and expense of magnetics is gone, the tradeoff is lower output current – typically 200 mA or less. On the other hand, it's a perfect solution for generating different voltages for portable devices, like handheld instruments and cell phones.

How an inverting switched-capacitor circuit works is a lesson in design simplicity (Figure 9). There are three steps to the inverter's operation. In Step 1, S1 and S2 are closed, which charges capacitor C1. Step 2, S1 and S2 are opened. This is done to prevent overlapping as switches S3 and S4 are closed, and the charge of C1 is transferred to C2. Watch the polarity as the transfer takes place. What used to be ground is now the negative output and the positive is grounded. S3 and S4 are then opened and the cycle repeats. Generally, the output voltage is not regulated, just simply inverted.

By arranging the switches and capacitors in other configurations, voltages can be doubled in either polarity. Several switched-capacitor converters provide voltage regulation by using a PWM to control the switches time on and time off – just like their inductive counterparts.

Typical Switched-Capacitor Applications

Switched-capacitor converters are typically simpler than their inductive counterparts. Very often they're used to create bipolar power supplies for battery-operated equipment. Figure 10 shows a few examples of switched-capacitor applications taken from Linear Technology's LT1054 data sheet; just one of the devices we'll look at for this exercise.

As usual, a small bypass capacitor is recommended on the input pin, typically a 2 uF tantalum. For unregulated circuits, the value of Cin and Cout should be equal. While the exact values of Cin and Cout are noncritical, the quality of the capacitor is; they must be low ESR capacitors to reduce ripple.

Since ESR is a function of the operating frequency, you need to make sure the capacitor's value is rated at the circuit's operating frequency. In general, the capacitor's ESR is inversely proportional to its physical size, so capacitors with larger capacitance values and higher operating voltage tend to reduce ESR.

However, not all manufacturers guarantee capacitor ESR in the range required by the circuit, which is why many vendors publish charts listing recommended capacitor types and manufacturers. See Figure 11 for a chart from Analog Devices' ADP3605 data sheet.

What's an OS-CON capacitor, you ask? I, too, was confused until I looked it up. Invented by Sanyo in 1982, the OS-CON is an aluminum electrolytic type capacitor with an organic semiconductive electrolyte. Some of its features are:

- Very low ESR
- Totally temperature independent
- Wide frequency range
- High ripple current capability
- Long life

Just the prescription for a switched-capacitor converter. And because of these properties, a much smaller capacitance value can be used as compared to a normal aluminum electrolytic capacitor. Moreover, bypass capacitors can often be eliminated in less demanding applications because the noise will be reduced by the OS-CON capacitor.

Multilayer capacitors are also frequently used in switched-capacitor applications. Multilayer capacitors are high-dielectric capacitors made by sintering ceramic materials at a low temperature. Its advantages are high capacitance in a small size and layered construction that makes it especially well-suited for surface mount fabrication (Figure 12).

Increasing Switched-Capacitor Output

In many cases, you can increase the output of a switched-capacitor converter by linking two or more devices. This is especially helpful when working with low-voltage, low-current converters, like the MAX829 from Maxim, which has a maximum rating of 5.5 volts in and 25 mA out. For higher output voltage, two devices can be cascaded, as shown in Figure 13. The unloaded output voltage is normally

$$-V_{out} = +V_{in} \times 2$$

but this value is reduced by the output resistance of the first device multiplied by the quiescent current of the second. When cascading more than two devices, the output resistance increases dramatically. As a rule, the larger the value of the charge-pump capacitor (Cp), the lower the output resistance – at least up to a point. Above a certain point, increasing the value of this capacitor has negligible effect on output resistance.

Paralleling switched-capacitor converters also reduces the output resistance – and increases the output current. The resultant output resistance is calculated using the formula

$$R_{out} = \frac{\text{Rout of a single device}}{\text{number of devices}}$$

Each device must have its own pump capacitor (Cp), but only one output capacitor (Cout) is needed for the parallel devices (Figure 13). The value of this

Weighing The Options

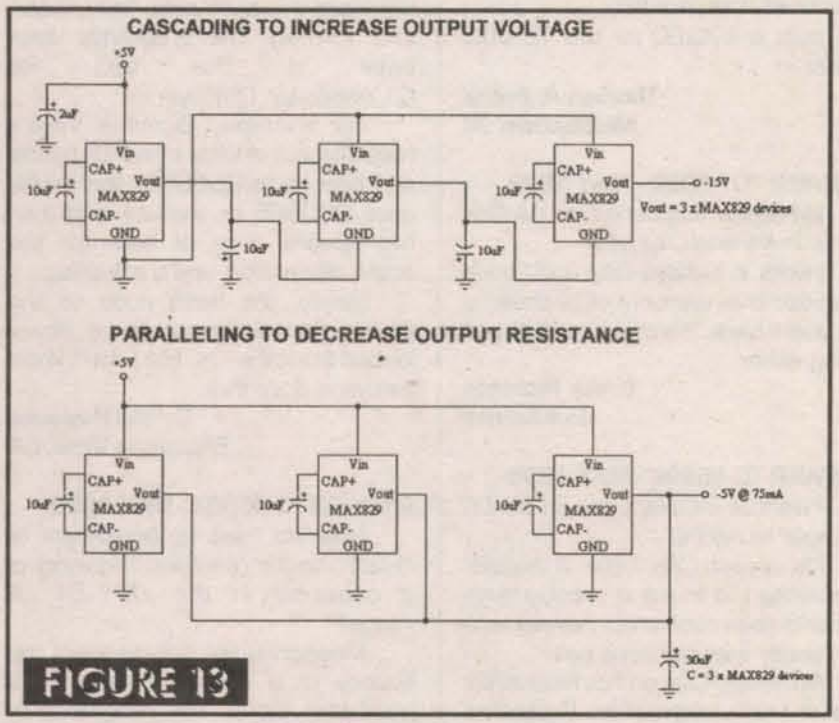

FIGURE 13

capacitor is directly proportional to the number of devices paralleled. For two chips, it's twice the original capacitance, three times for three chips, and so forth.

Just Touchin' The Basics

There's a lot more that I can say about switching converters, but space doesn't permit. You can obtain more information on switching regulators from the data sheets cited from http://www.questlink.com and the answers you'll find in this month's Electronics Q & A column. Want even more? Download the f5.pdf file, a whitesheet on switching regulator technology written by National Semiconductor, that's posted on our web site (http://www.nutsvolts.com). **NV**

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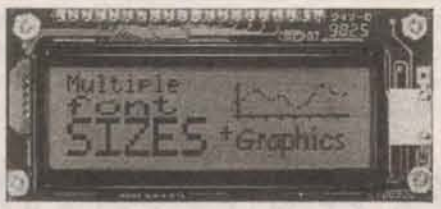
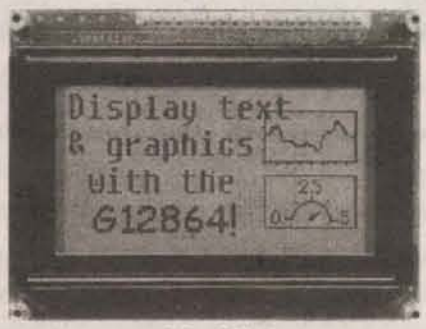


(3.2 x 1.4 in.)



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